1.0

2.8 | 2.5

3.2 | 2.2

1.1 | 2.0

1.8

1.25 | 1.4 | 1.6

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

ARTIFICIAL SATELLITES, MINOR PLANETS, AND THE ETS

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Group 94

PROJECT REPORT ETS-53

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ABSTRACT

This report summarizes the successful modification of Lincoln Laboratory's Experimental Test System hardware and software for the detection and discrimination of asteroids rather than artificial satellites. The minor planets are found by exploiting their proper motion and the limiting magnitude is roughly $B = 17^m.5$. The complete observing cycle, including the $2 - 3^m$ measurement of position, requires about four minutes at present. The commonality of asteroids and artificial satellite observing, searching, data reduction, orbital analysis, and lightcurve analysis is stressed.

BRIGHTNESS MAGNITUDE = 17.5

SEC

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I. ASTEROIDS AND ARTIFICIAL SATELLITES

The ETS exists to observe artificial satellites by their reflected sunlight and to detect and discriminate them by their large ($\sim15"$/sec) proper motions. Once found we record their positions for subsequent recovery by dead-reckoning, for the initial generation of orbital element sets, and for the refinement of an existing orbital element set. We also record various photometric data, both wide-band and multi-color, to detect any lightcurve variations and for classification purposes. In particular, the various periodicities in a satellite's motion relative to its center of mass (spin period, precession period), information concerning its size, shape, and the nature of its surface, and the satellite's orientation are desired data. We also search for lost and unknown satellites in a variety of ways. See reference 1 for a general summary.

Each of the above types of data acquisition and analysis have been, and continue to be, performed for asteroids (or minor planets). The first searches were conducted in 1800; over 2200 asteroids are now permanently catalogued and nearly 2000 new objects are discovered yearly. That the relationship between artificial satellites and minor planets goes fairly deep should not be surprising. Asteroids are natural satellites of the Sun shining by reflected sunlight. They come in a large variety of sizes, shapes, surface reflectivities,

spin periods, orientations, etc. They and comets span the limits of solar system orbital element space. This commonality of aspects implies a commonality of observing techniques, analysis techniques, and the fruitful cross-fertilization of the two fields.

So far this flow has been one way - from minor planet work to artificial satellite work. We want to extend minor planet research with the specific intention of advancing our capabilities in the field of artificial satellite work - especially with regard to initial orbit generation, search techniques, lightcurve analysis, and applications of multicolor photometry.

Although the geocentric proper motion of an asteroid is fairly small ($\sim$50"/hr), one can be discriminated by this characteristic. Instead of long time exposures of photographic plates, which when developed show a trail for an asteroid, we have modified the hardware and software at the ETS for the real time detection of minor planets (references, 2, 3, and 4). In the remainder of this report, which is the documentation of a successful observing technique and not a detailed report of results or future expectations, we discuss the equipment, the software, how we find asteroids, and what we do with them. There is also a brief discussion of the concept of limiting magnitude in this context and how we arrived at one.

II. HARDWARE

A. Design Considerations

To discriminate minor planets from stars by their proper motions the basic electronic hardware associated with the video imaging system is the same as for an artificial satellite moving target indicator (see reference 5). The design of such a system is schematically shown in Fig. 1. As with its radar counterpart, the essential features are a storage medium, a delay line, and the capability to subtract the current signal from the stored one. Detection is performed after the difference image is obtained. For minor planets we serve as the detector -- hence our system is not automated in this respect.

The purpose of the delay line is to allow for a sufficiently long time interval during which the celestial object can traverse several (clearly at least 2) resolution elements of the camera tube target. For the artificial satellites within GEODSS coverage a typical delay time is $\simeq 0.5s$ (e.g., resel size $\simeq 3''.5$, angular speed $\simeq 15''/sec$). The extremes would be $0^s.02$ and $1^s.5$. Since a typical asteroidal geocentric angular speed is $\lesssim 50''/hr$ the appropriate delay interval is in excess of 9 minutes. Hence, were this mode of operation followed, neither efficiently conducted searches nor efficiently performed positional measurements would be possible. Clearly it's much more effective to use the delay time
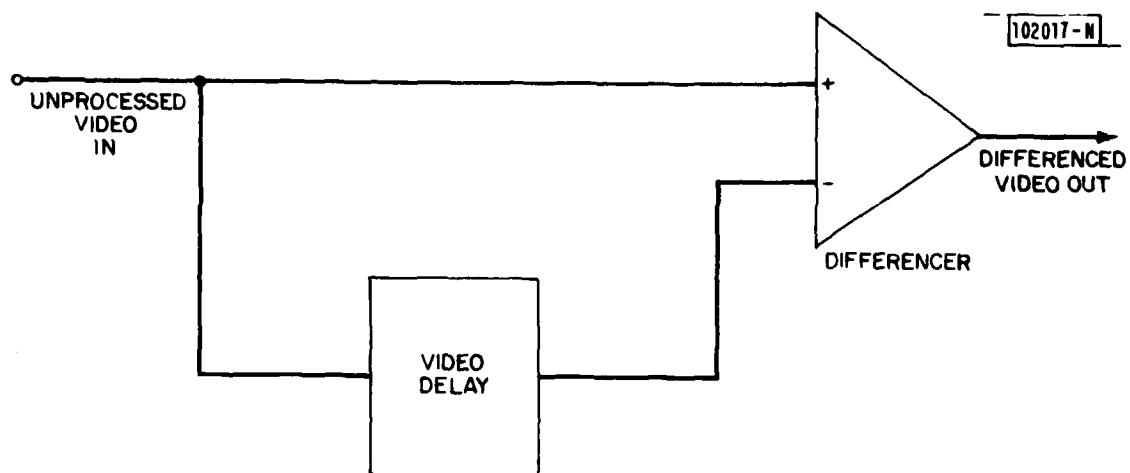
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                                          102017-N
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UNPROCESSED
VIDEO
IN

DIFFERENCED
VIDEO OUT

DIFFERENCER

VIDEO
DELAY

Fig. 1.   Basic Moving Target Indicator system block diagram.

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to look for other minor planets and this implies a "delay line"

capable of storing as many video frames as we can acquire during

the $\lesssim$9 minute interval. Further, since 3-5 resels are much

better than two and many asteroids move even slower than 50"/hr

the "delay line's" storage capability should be at least 50

frames. Moreover it would be extremely convenient to be able

to access any of these frames at random. Therefore, the simple

delay line of Fig. 1 will be replaced by a random access

multiple frame video storage device.

Storage tubes can be immediately eliminated as the storage

medium both because of cost ($\sim$\$4,000/frame) and the difficulties

of matching the outputs of the necessary number of storage

tubes with the live video. Digital solid state memory devices

could be designed with multiple frame storage capacity and with

very good frame-to-frame output equivalence. Again their cost

is prohibitively high (<\$7,000/frame). Given the tentative

nature of this type of observing, the availability of an analog

disk storage device within Lincoln, and the quality of our

video tape recorders, we decided that the special purchase of

neither a digital disk storage device nor a modern studio grade

video tape recorder could be justified. However, were we to

inaugurate a minor planet search and observing program from the

beginning,we would need to examine the relative advantages of

the video tape recorder, the digital disk video storage system,

and the analog disk video strage system.

The least expensive system is the video tape recorder which has excellent archival capabilitites. Modern (studio grade) units also have the capability to search the video tape for a specific segment. This is awkward to do though and not very efficient.

In the case of digital disk storage devices recent advances have improved their frame-to-frame stability, their reliability, and the size of their memory. Now 5-10 seconds worth of video data (150 - 300 frames at the television camera refresh rate of $1/30^S$) can be stored. They are 2 - 3 times as expensive as analog devices though.

Analog devices cost $\sim\$60$/frame and have the capacity to store several hundred frames. Random access is available and nearly instantaneous. The disadvantages of such units reside in the mechanical aspects of the unit -- particularly in the read/write head-disk interface. One has to replace the head at ~ 100 hr intervals as well as the disk itself at roughly this time interval. Disk replacement, when "floppy" disks are used, has become much simpler but the head cleaning and replacement processes are time consuming. Also, because of flux variations within the disk coatings, there are differences in the signal level both line-to-line and frame-to-frame.

B. The Prototype System

A simplified block diagram of the moving target indicator system we've devised is shown in Fig. 2. The delay line of Fig. 1 has been replaced by two elements, an analog disk video storage unit and a video integration/storage device. The latter is used to increase the unprocessed video signal level above the minimum signal-to-noise ratio necessary to recover it from the storage medium. This increases our limiting magnitude with a negligible loss of efficiency (see Subsection C below). There are two basic types of such devices -- analog and digital.

An analog storage tube scan converter has been used at the ETS for several years. Because of imperfections in the silicon target storage element, principally blemishes and variable response across the target face, the complete can-cellation of successive video frames is difficult to accomplish.

Digital image processing and storage systems are more attractive than analog ones because they don't suffer from these defects and they are programmable. The one we've used (again principally because of immediate availability within Lincoln) is a Quantex Corporation DS-20 (Fig. 3). It stores 12 bits/resel of amplitude information and has a 512 x 512 resel format. Among other tasks it can be programmed to difference frames, store them or snatch them. Coupled with this is our analog disk video storage medium, an Echo Science
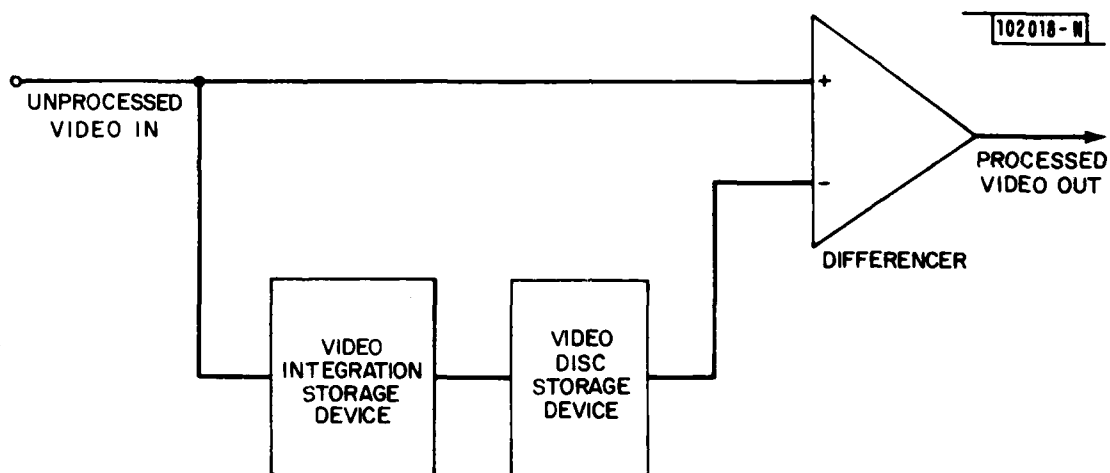
Fig. 2. Simplified Minor Planet MTI block diagram.

Company EFS-1A Discassette Frame-store color video recorder.
This is also shown in Fig. 3. The third unit in Fig. 3 was used
to synchronize the signals but has proved unnecessary.

The video differencing itself could be accomplished by a
simple high frequency operational amplifier -- if all system
delays and signal level shifts could be neutralized. In practice
this is extremely difficult to do. Hence the following alternative
was devised: The Quantex DS-20 digital video processor is
switched from its recording function when the reference (i.e.
original) frame is stored to that of a differencer between the
Echo EFS-1A video disk storage unit and the comparison (i.e.
the subsequent) frame. This is illustrated in Fig. 4 which is
a full block diagram of the prototype minor planet moving target
indicator.

Additional equipment to provide discrimination includes
video distribution amplifiers for video isolation within the
processing equipment and the appropriate coaxial switches.
Table 1 contains a complete list of all of the discrimination
hardware. As mentioned above one of us serves as the detection
instrument. Our operating characteristics are discussed in § III.

C. Method of Operation

The Appendix contains a complete step-by-step set of
operating instructions for the system. Here a brief overview
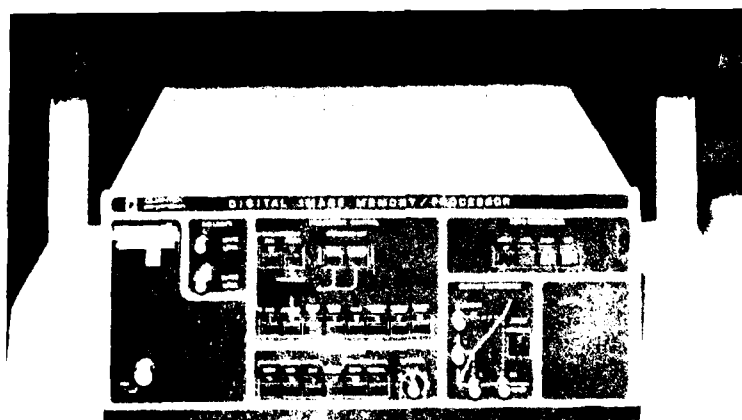is given. With reference to Fig. 4, during the recording phase
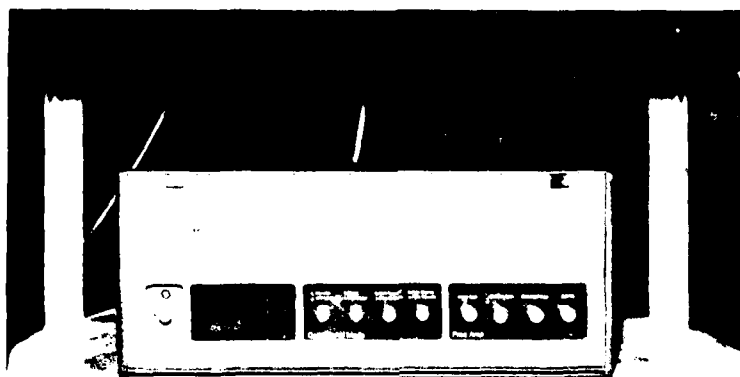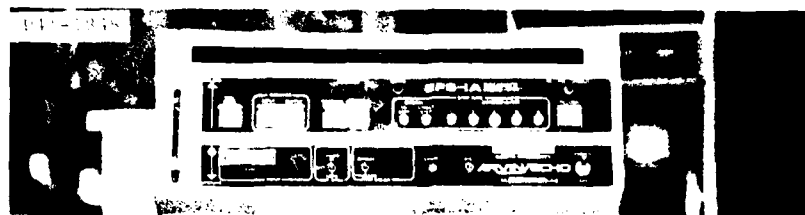
Fig. 3. The Minor Planet MTI hardware. The Arvin Echo EFS-1A
is at the top and the Quantex DS-20 is on the bottom. The time
based corrector (in the middle) is no longer used.

TABLE I

EQUIPMENT LIST

Disk Storage Unit. . . . . .ARVIN Echo
                                              Model EFS-1A

Digital Storage and
Integration Unit. . . . . Quantex
                                              Model DS-20

Time Base Corrector. . . . . .Microtime
                                              Model 1020

2 ea. VDA (Video Distribution
Amplifier). . . . . Telemation
                                              Model TVA-525

2 ea. Video Switch. . . . . Matrix Systems Corp
                                              7104

Fig. 4. Full block diagram of our Minor Planet MTI. The video switches are shown in the record positions.

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of the operations video switches 1 and 2 are in position #1.
The telescope is pointed, set into sidereal drive, and the
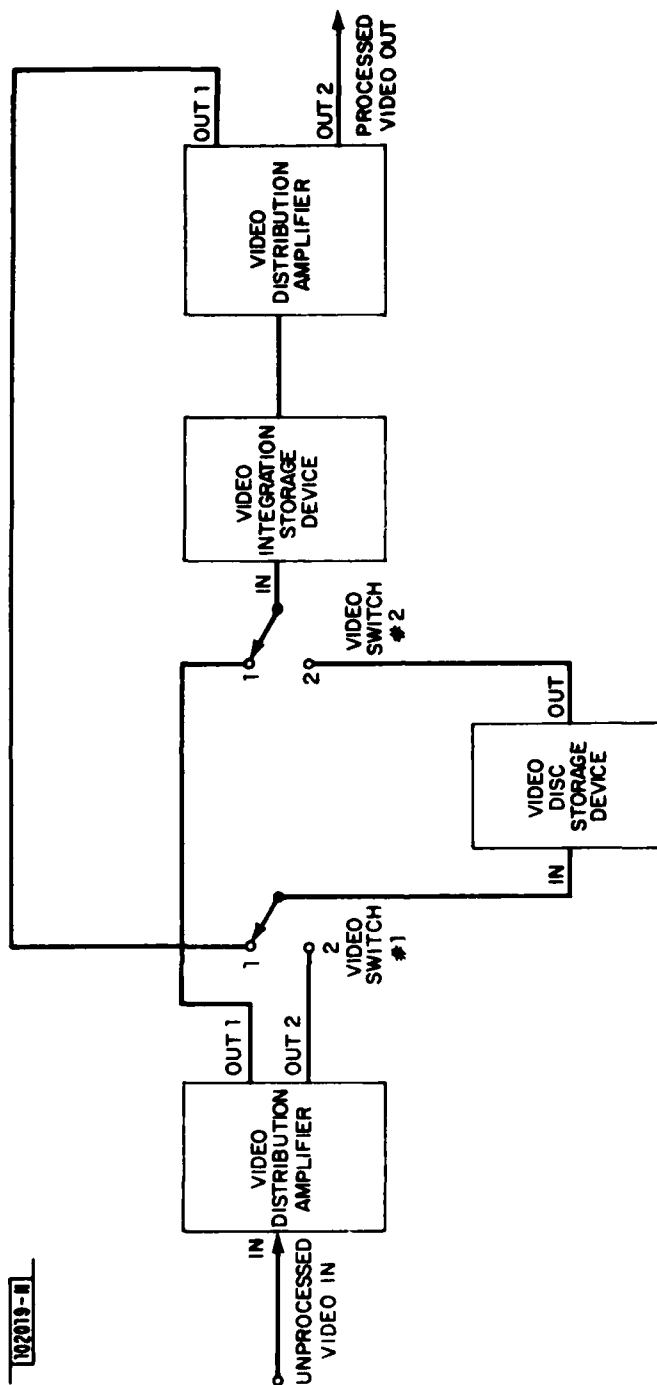digital storage and integration unit (the DS-20) activated.
It integrates until the saturation level is reached within a
resel (typically $\sim 2^s$). This integrated image is stored, as
a single frame, in the analog disk video storage device (the
EFS-1A). The telescope is moved to the next position and
this process repeated. This continues until the appropriate
time interval ($\sim 30^m$) has elapsed and we then return to the
original field. We now recover the appropriate frame of stored
data and place video switches 1 and 2 into the #2 position.
We also reprogram the DS-20 for the differencing mode. The
first step is to repeatedly sum the reference frame in the
DS-20 until saturation occurs. This is equivalent to signal
averaging and is necessary if the full recovery of low signal-
to-noise (e.g. faint) images is to occur. It also reduces
the noise levels inherent in the video recovery process within
the EFS-1A itself. Now live video (the comparison field) is
fed to the DS-20 and the differencing performed. Constant
objects are cancelled at this stage appearing only at the back-
ground level. An object that has moved appears twice, once as
a negative (or dark) image from the reference frame and once as
a positive (or light) image from the comparison frame. Figures
5-9 illustrate this.

We will be the first to admit that Figs. 5-9 aren't overly impressive. There is clearly incomplete cancellation due to field misalignment and distortions in the camera tube. However, these pictures were made by overprocessing some video tape recordings (to increase the contrast), playing the result through a television monitor, and then photographing the television monitor screen. The original video tapes were made at the instant of detection (for purposes other than the generation of Figs. 5-9) and more than anything else they illustrate that for asteroids this bright ($\sim 15^m$) discrimination is instantaneous. The image at the telescope console that the (human) detector sees is much better than Figs. 5-9 would indicate. The next section describes our efforts to determine a precise and meaningful limiting magnitude.

Fig. 5. Detection of 855 Newcombia (nearest center) and another asteroid. On this and the following four figures the asteroid is in the lower right-hand quadrant and the white dot is below and to the right of the black dot.
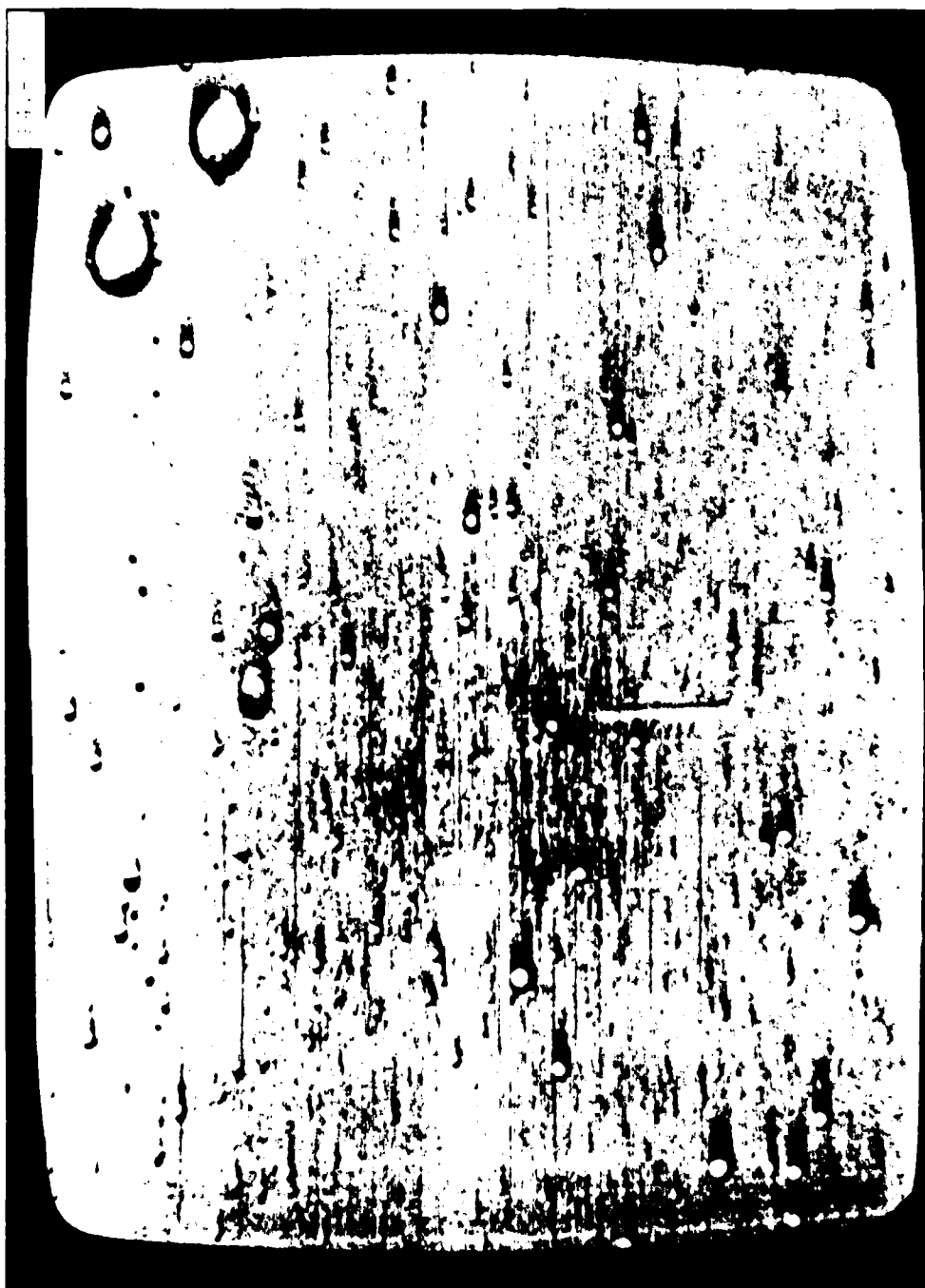
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Fig. 6. Detection of 265 Anna.

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Fig. 7. Detection of 1391 Corelia.

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Fig. 8. Detection of the Trojan asteroid 1867 Deiphobus.
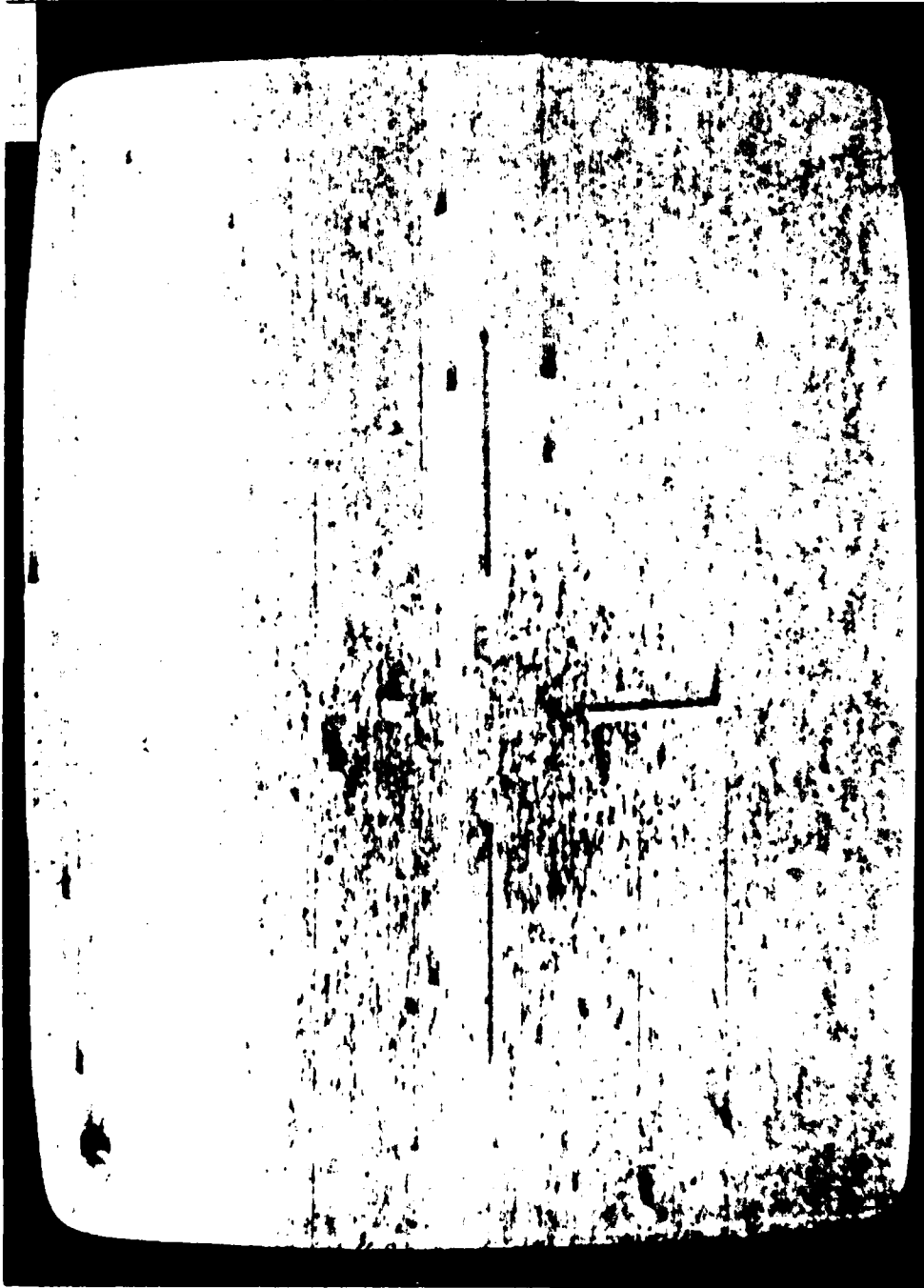
Fig. 9. Detection of 1684 = 1951 QE.

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III. PHOTOMETRY

The measurement of the brightness of a celestial object
is a conceptually rather straightforward process which in
practice is subject to a variety of errors which are difficult
to correct. Only a brief sketch of the problem will be
given here (see references 6-8). For reasons mentioned below,
the idea of limiting magnitude is somewhat ill defined and so
it is not sensible to expend great efforts in order to achieve the
utmost in precision. Thus, although care must be taken to ensure
that all effects are considered, the actual treatment of each
can be rather "quick and dirty". The situation is further
ameliorated by using differential photometry. This technique
both speeds the measurement and improves precision considerably.
The price paid is the risk of introducing small systematic errors
which for this particular case are of no consequence.

Measurements are made by pointing the telescope at the
object of interest and measuring the resulting photo-count
rate n. The measurement is then put on a standard astronomical
system via

$$m \equiv \zeta - 2.5 \log n - \delta \qquad (1)$$

Here m is the brightness in magnitudes, ζ is the instrumental
zero point, and δ is a correction for atmospheric extinction
which is a function of amount of air through which the measurement
is made, X. This so-called air mass is a geometric function

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of the pointing direction. Since the measurement of n is made
with an instrument having a particular spectral response, it is
usual to subscript all the quantities in Eq. (1) to indicate
which response profile is meant. Thus m_v indicates magnitudes
measured with the visual response profile defined by Johnson and
Morgan (reference 9). We will suppress this subscript until it
is needed later on. The difference between brightnesses expressed
on different systems and the extinction correction are both dependent
on the spectral characteristics of the object being measured.
The spectral characteristics are parametized by a color-index c
which is the difference between two magnitudes.

In differential photometry two objects are measured. The
object of interest or "program" object and a nearby comparison
"standard".   Thus

$$m_p = \zeta - 2.5 \log n_p - \delta_p$$
$$m_s = \zeta - 2.5 \log n_s - \delta_s$$

Combining these gives

$$m_p = m_s - 2.5 \log (n_p/n_s) - (\delta_p - \delta_s) \qquad (2)$$

The value of m_s is known (it is the "catalog" value) so there
only remains the evaluation of the extinction term. If the
comparison object is properly chosen, then both X and c are
approximately the same for program and standard object, and it
makes sense to expand δ as a power series:

$$\delta_p \simeq \delta_s + \left.\frac{\partial\delta}{\partial X}\right|_{X_s} (X_p - X_s) + \left.\frac{\partial\delta}{\partial c}\right|_{c_s} (c_p - c_s) \qquad (3)$$

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In most circumstances the higher derivatives may be safely dropped. Inserting this in Eq. (2) yields:

$$m_p = m_s - 2.5 \log (n_p/n_s) - (X_p - X_s)\frac{\partial \delta}{\partial X}$$

$$- (c_p - c_s)\frac{\partial \delta}{\partial c}$$

A fairly good approximation for $\frac{\partial \delta}{\partial c}$ may be obtained from a mathematical model or at worst a few measurements. In either case, the size of the effect is usually quite small. The value of $\frac{\partial \delta}{\partial X}$ must be obtained at the time of the measurement. Under conditions which astronomers call "photometric" $\frac{\partial \delta}{\partial X}$ remains constant for many hours over the entire sky and the higher order terms in Eq. (3) are in fact very small. Under poor conditions neither of these nice characteristics is true. A quick and dirty value for $\partial\delta/\partial X$ may be obtained from:

$$\frac{\partial \delta}{\partial X} = \frac{\zeta - 2.5 \log n_s - m_s}{X_s}$$

Since $(X_p - X_s)$ should be small it is not necesssary for this estimate to be of extremely high accuracy. In the case of poor conditions fairly good results can be obtained by making $(X_p - X_s)$ very small. If $\frac{\partial \delta}{\partial t}$ is appreciable, then one is likely to do better using long term averages for the other two derivatives and keeping $(X_p - X_s)$ and $(c_p - c_s)$ as small as possible. In extreme cases it is even possible to use historical values on n_s. This, in fact, was the technique used to obtain the values reported here. For faint objects the situation is further complicated by the presence of a large background flux and the contribution from

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the dark current.

In astronomical photography the concept of a limiting mag-
nitude is well defined and depends solely on the physical properties
of the system. Depending upon other variables, the limiting
magnitude may be achieved in a few minutes or many hours exposure.
This sort of limiting magnitude is not particularly applicable to
the case at hand. The point of these experiments was to find
objects of unknown location by searching for them. Increasing the
exposure thus has a strongly negative effect in that it sharply
decreases the area which can be searched. Since the search is
conducted in real time it is also necessary to include extra
time for an operator to detect any object which has been dis-
criminated by the hardware. Clearly the desired goal is to
maximize the probability of finding a suitable object. The
brighter the object sought the more quickly it can be found and
the greater the searched area can be. The fainter the object
sought the more of them there will be. We may instead think
of a practical limiting magnitude. Our experience has been
that down to some level of brightness any candidate may be
found within about twenty seconds and that very few (presum-
ably slightly fainter) are found by extending the looking
time to several minutes. In this regard it is possible to draw
on our extensive experience with satellite detections. Changing
the operational parameters of the video system makes it easier

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to find marginal detections, but to a large extent this is merely
a trade between exposure time and examination time to no overall
benefit.

Based on the preceding consideration, we have decided
to accept as a practical limiting magnitude the brightness of
the faintest objects which are found within say 30 seconds,
with the "standard" hardware configuration described above.
It is to be expected that slowing the search would allow detection
of a few tenths of a magnitude fainter, but that this could
not be justified unless there were reason to believe that the
distribution of brightness was much steeper than anticipated
or that the appropriate search region was considerably smaller
than we currently feel it is.

The night on which the brightness measurements were made
was of marginal quality - a space of a few hours between two
completely clouded periods. The period of measurement seemed to
be fairly uniform until the clouds returned. This can be quantified
by the internal consistency of multiple measurements which showed
the measurement error to be only slightly larger than could be
expected from the counting statistics alone. It is this measurement
error which is quoted below. An additional error source - error
in the correction for extinction - is expected to be negligible
compared to the measurement error for threshold objects. Measure-
ments of the two faintest asteroids found gave values of
$m_x = 16^m\!.4 \pm 0^m\!.3$ and $16^m\!.6 \pm 0^m\!.2$. The x-subscript denotes

measurement through a filter commonly used at the ETS which has a central wavelength of 0.67μ. The x-filter magnitude is defined so that $m_v = m_x$ for solar colored objects. Thus we estimate the limiting V-magnitude at $m = 16\overset{m}{.}7 \pm 0\overset{m}{.}2$ or, as is commonly quoted, a limiting B-magnitude of $m_b = 17\overset{m}{.}6 \pm 0\overset{m}{.}2$.

IV. ASTROMETRY

The fundamental source of data on asteroid positions and orbital element sets is the Ephemerides of Minor Planets (EMP) published yearly by the Institute of Theoretical Astronomy at Leningrad. Until the 1980 edition the epoch of an individual orbital element set depended on the last time someone refined that orbit. Hence many element sets were quite old (1950s or 1960s with a fair number 10 - 20 years earlier). Therefore, without sophisticated numerical integration, these are useless for predicting positions. Also, as asteroids dim rapidly with increasing phase angle (about $0^m.03$/degree), observations are most frequent near opposition. Therefore EMP includes geocentric ephemerides at 10^d intervals (for a time span of 70^d) centered on the instant of opposition for each asteroid undergoing opposition that year. These are in the form of 1950.0 right ascension (to $\pm\ 0^m.05$) and declination (to $\pm\ 0'.5$) at 0^h E.T. A simple computer program, which allows the user to specify the date of interest and the brightest asteroid of interest, was written to plan the observing. Since the ephemerides had to be put into machine readable form this aspect represented the huge bulk of the work.

The output of the program, for all those asteroids undergoing opposition within 35^d of the requested date and sufficiently faint, is current epoch geocentric right ascension and declination, their rates, the position angle of the motion

(to $\pm$ 5°), the compass direction of the motion (e.g. NE or W), the last year seen, and the time to move 5" ($\pm$ $0^m.5$). This is given for both 0^h and 12^h E.T. of the requested date. The last quantity is indicative of the return time to the field (although the time to move 10" is probably better). The position and angular velocity were obtained by Lagrangian interpolation (3-point).

Starting with the 1980 volume of the EMP osculating orbital element sets for a modern date (currently 0^h E.T. December 27, 1980) will be provided for each numbered minor planet. These can be used within a year or two of epoch to provide $\pm$ 5' pointing - the accuracy of the 10^d ephemerides. We already have this information in machine readable form and when coupled with the daily ephemeris of the Sun (already at the ETS) we can now treat pointing for asteroids in the same fashion as is done for artificial satellites. The software to do this is being written now.

Once we've found a minor planet we obtain its position using standard ETS procedures (reference 10). These are then reduced and published in the Minor Planet Circulars. Since there are about 5000 asteroids visible to us and they are (principally) confined to a belt 30° wide it follows that we will see, on the average, 0.5 asteroids/square degree. Since our zoom field is about 0.1 square degrees, the simultaneous

appearance of two minor planets in the same field should be
rare. Hence the need for an on-line identification procedure is
minimal. Of course, we've already had two objects in one field
(see Figure 5).

APPENDIX

I. EQUIPMENT INITIALIZATION

Move the coaxial switches to position #1

A. Quantex Video Processor Setup

    1. Program as follows

        a. Push HOLD button

        b. Push AUTOSTOP/SUM FULL button on

        c. Push LEARN button on

        d. Push SUM button

        e. Push WAIT button

        f. Push MEMORY CLEAR button

        g. Push the RUN button twice

    2. Video output set as follows

        a. Set SOURCE = MEM

        b. Set GAIN = AUTO

        c. Set POLARITY INVERT to non-inverted

B. Arvin Echo Video Disk Storage Setup

    1. Turn disk drive on

        a. Push MONITOR/OUTPUT switch

        b. Set STEP RATE to NO STEP

    2. Adjust video LEVEL ADJUST to a center null position
       on the video meter

    3. Synchronization

        a. In EXT mode if an external synchronization
           is available or

b.   in the VIDEO IN mode if not

         4.   Set color switch to DIRECT position

         5.   Set E-E switches to off (down) position

   II.   FRAME STORAGE

         A.   Quantex

              1.   Push the RUN switch and wait until the WAIT LED lights

         B.   Arvin Echo

              1.   Position read/write head to desired frame number (1-400)

                   a.   Push ERASE button

                   b.   Push RECORD button. Monitor video disk output
                        for rewarding quality. If necessary repeat
                        II B 1a & b until a good recording is made

                   c.   Repeat II A & B for each desired field

                        1.   When done go to III

   III. MTI

         Move the coaxial switches to position #2

         A.   Quantex

              1.   Set SOURCE = DIF

              2.   Set GAIN = AUTO

              3.   Set POLARITY INVERT to inverted

         Position telescope appropriately

         B.   Arvin Echo

              1.   Position read/write head to desired frame number

              2.   Set monitor switch to OUTPUT

         C.   Discrimination

              1.   Push RUN on the Quantex

2. Set monitor switch to INPUT on the Arvin Echo

3. Move telescope, if necessary, to align images

D. Detection

Search for matching pairs of black and white dots

ACKNOWLEDGMENTS

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asteroids	artificial satellites	ETS
orbital analysis	lightcurve analysis	GEODSS

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

This report summarizes the successful modification of Lincoln Laboratory's Experimental Test System hardware and software for the detection and discrimination of asteroids rather than artificial satellites. The minor planets are found by exploiting their proper motion and the limiting magnitude is roughly $B = 17^m5$. The complete observing cycle, including the $2 - 3"$ measurement of position, requires about four minutes at present. The commonality of asteroids and artificial satellite observing, searching, data reduction, orbital analysis, and lightcurve analysis is stressed.

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